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# DIFFUSION BONDING OF TITANIUM ALLOYS

Third Quarterly Report


By

C. A. Smith
E. L. Reed




May 1, 1967


ATOMICS INTERNATIONAL
A Division of North American Aviation, Inc.
Canoga Park, California



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## ABSTRACT

The program attempts to develop an understanding of the diffusion bonding of titanium alloys; in particular, the alloy Ti-6Al-4V. The accomplishments of the third quarter of the program are as follows:

1) A series of tensile and bend tests has been completed. These tests showed trends which were in reasonable agreement with the shear tests performed during the second quarter.

2) Additional shear tests have been performed to extend the range of variables to greater pressures and shorter bonding times than those reported for the second quarter.

3) Examination of bond line photomicrographs indicates a correlation between bonded length and relative tensile strength. This correlation may find practical use in estimating bond quality.

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FIGURES

## TABLES

## I. TENSILE AND BEND TESTS

### A. PREPARATION OF SPECIMENS

The preparation and testing of eight butt diffusion bonded Ti-6Al-4V alloy specimens was completed during the quarter. Details of the graphite tooling fixture used to hold the specimens during bonding are shown in Figures 1 and 2. Figure 1 shows the graphite tooling with two bonded specimens in place after a typical run. The white base plate is an alumina ceramic used to support the fixture during the bonding cycle. A photograph of the vacuum furnace used for diffusion bonding was exhibited in the first quarterly report.* Figure 2 shows the fixture assembled with the top load plate in place. Stainless steel weights were placed on top of the load plate after the assembly had been placed inside the furnace. The total weight of the top plate and rings was adjusted to obtain a specimen bonding pressure of 100 psi.

Figure 3 shows typical pieces of the titanium alloy before and after butt diffusion bonding. The bonded specimen on the right shows a bond line at the joint because of a slight bevel on the edges. The surfaces were ground to remove any surface imperfection at the joint interface.

Specimens were butt diffusion bonded under the following sets of conditions:

Butt Diffusion Bonding Runs

| Spec. No. | Bonding Conditions | Best and Poorest Vacuum Readings | Remarks |
|---|---|---|---|
| 1S | 1500°F-1 Hr.-100 psi | $2 \times 10^{-5}$ to $8 \times 10^{-4}$ Torr | No bond obtained |
| 4S | 1500°F-1 Hr.-100 psi | $7 \times 10^{-6}$ to $4 \times 10^{-5}$ | Very poor bond |
| 3S | 1600°F-1 Hr.-100 psi | $2 \times 10^{-5}$ to $4 \times 10^{-5}$ | Bonded |
| 5S | 1600°F-4 Hr.-100 psi | $1 \times 10^{-5}$ to $3 \times 10^{-5}$ | Bonded |
| 2S | 1700°F-1 Hr.-100 psi | $2 \times 10^{-5}$ to $6 \times 10^{-5}$ | Bonded |
| 6S | 1700°F-4 Hr.-100 psi | $2 \times 10^{-5}$ to $5 \times 10^{-5}$ | Bonded |

Little or no bonding was achieved at 1500°F but good appearing bonds were obtained at 1600°F and 1700°F. Figure 4 shows four specimens that were bonded at 1600°F and four specimens that were bonded at 1700°F. Note that the bond

* Smith, C. A., and Reed, E. L., "Diffusion Bonding of Titanium Alloys," First Quarterly Report. U.S. Army Materials Research Agency Report No. CR66-10/1.

line is visible in the center of each specimen. After grinding to remove the slight edge bevel the bond lines were no longer visible to the naked eye. One specimen from each set of bonding conditions was machined into tensile specimens. Figure 5 shows a photograph of these specimens before tensile testing. Note that the bond interface is no longer visible after surface grounding and machining. Figure 6 shows these specimens after tensile testing. The small black circles on three of the specimens outline the 2 in. gauge marks that were used to determine total elongation. Gauge marks also are visible on specimen 6S.

## B. ROOM TEMPERATURE TENSILE TESTS

The results of the tensile tests are listed in Table 1. Specimen 3S-B bonded at 1600°F for one hour showed poor tensile strength and no elongation, but four hours bonding time at 1600°F (Spec. 5S-B) resulted in a significant strength improvement even though the elongation was still nil. (The specimen pressure in these butt diffusion bonding tests was the same as for the majority of the specimens diffusion bonded in the vacuum hot press equipment.) Bonding at 1700°F for either one hour or four hours produced joint tensile strengths greater than 90 percent of the parent metal strength. Four hours at 1700°F resulted in an ultimate tensile strength increase of 4,300 psi as compared with the sample bonding cycle of one hour at 1700°F. Both of the specimens bonded at 1700°F showed 13% elongation in a gauge length of 2 in. compared with 11.8% for the parent metal.

Small pieces of the alloy were cut from the joints of the tensile specimens before they were machined. The microstructure of these different specimens showed an interesting correlation of bond appearance with the ultimate joint tensile strengths. Figures 7, 8, 9 and 10 show photomicrographs of these joints. Portions of these same areas are shown at a magnification of 500X in Figures 11, 12, 13 and 14. Referring first to the photomicrographs at 100X observe that in Figure 7 there are very few areas showing bonding across the interface after bonding at 1600°F for one hour. Here the ultimate tensile strength of the bond was only 49,700 psi. Figure 8 shows a number of areas in the sample that were bonded at 1600°F for four hours where complete bonding across the interface has occurred; the resulting joint strength was increased to 122,300 psi. Similarly, in Figure 9 only a few unbonded spots are visible and the bond strength has increased to 133,200 psi, while in Figure 10 only two or three very small unbonded spots are perceptible. Here the ultimate tensile strength was 137,500 psi, or 94.7% of the parent metal strength.

A comparison of the microstructures with the corresponding joint strengths is even more striking at 500X (Figures 11, 12, 13 and 14). A rough approximation of the percent of bonded length was made from each photomicrograph. The results are listed below and compared with the percent of parent metalultimate strengths observed:

| Spec. No. | Bonding Parameters | Apparent Percent Bonded | Percent of Parent Metal Strength |
|---|---|---|---|
| 3S | 1600-1 Hr.-100 psi | 47% | 34.2% |
| 5S | 1600-4 Hr.-100 psi | 72 | 84.2 |
| 2S | 1700-1 Hr.-100 psi | 84 | 91.7 |
| 6S | 1700-4 Hr.-100 psi | 94 | 94.7 |

These results show a good correlation considering the short lengths of bond line observed at 500X.

C. ROOM TEMPERATURE BEND TESTS

Room temperature bend tests were performed on the second set of specimens from the butt diffusion bonding series. Bend tests also were made on three specimens of the parent Ti-6Al-4V alloy which were machined and finish ground to the same dimensions as the bonded specimens. The results of these tests are shown in Table 2. The increase in bend strengths showed the same pattern as for the tensile tests. A bend span of 3.0 inches was used. Maximum flexural bend strength was calculated from the following formula:

$$F = \frac{1.5\ PL}{bh^2}$$

where:

- F = flexural bend strength
- P = maximum bend load in pounds
- L = span in inches
- b = specimen width in inches
- h = specimen thickness in inches

Note that the flexural strength values were significantly higher than the tensile strength values, particularly for the parent metal and for the tests performed at 1700°F. This behavior is not unusual for ductile materials. However, the values are approximately the same in flexure and tension for specimens 3S and 5S where the specimens exhibited no ductility (brittle behavior).

## II. SHEAR TESTS

Shear tests were performed on two specimens hot press bonded at 650 psi for one hour at 1540 and 1640°F, respectively. Also two specimens were hot press bonded at 100 psi for 1/2 hour at 1440°F and at 1470°F. The latter specimens were prepared to fill in an apparent gap in the deformation (vs.) shear strength curve presented in the last report. The average shear strengths of these specimens and the shear strengths of the respective parent metal specimens are shown in Table 3. Specimen deformations also are listed. Note that the 650 psi runs showed a large amount of specimen deformation and joint strengths equivalent to those of the respective parent metal pieces. The specimens bonded at low pressure for short times showed the same amount of specimen deformation (0.0025 in.), yet considerable difference was observed in their average shear strength values.

Figures 15 and 16 show the microstructure of a section of specimen 2 HP at 100X and at 500X magnification. Similar photomicrographs of a section of specimen 3 HP are shown in Figures 17 and 18. Complete bonding and grain growth across the interface is evident in both specimens.

## III. PLANS FOR THE FOURTH QUARTER

No laboratory work is contemplated for the fourth quarter. Data analysis and work on the mathematical model will continue. Preparation of the topical report will begin.

TABLE 1

ROOM TEMPERATURE TENSILE AND YIELD STRENGTH
OF BUTT DIFFUSION BONDED Ti-6Al-4V ALLOY SPECIMENS

| Specimen Number | Bonding Conditions | Elongation (% in 2 in.) | Yield (0.2% Offset) | Ultimate Tensile | Percent of Parent Metal (U.T.S.) |
|---|---|---|---|---|---|
| 3S-B | 1600°F-1 Hr.-100 psi | None | None | 49,700 psi | 34.2% |
| 5S-B | 1600°F-4 Hr.-100 psi | None | None | 122,300 | 84.2 |
| 2S-B | 1700°F-1 Hr.-100 psi | 13.0% | 130,600 psi | 133,200 | 91.7 |
| 6S-B | 1700°F-4 Hr.-100 psi | 13.0 | * | 137,500 | 94.7 |
| Parent Metal | Untreated | 11.8 | 137,900 | 145,200** | 100.0 |

* Extensometer failed. No data obtained.

** Average of three specimens.

TABLE 2

BEND STRENGTH OF BUTT DIFFUSION BONDED Ti-6Al-4V SPECIMENS.
SPECIMEN DIMENSIONS 1.0" WIDE BY 7.6" LONG BY 0.16" THICK.
BEND SPAN, 3.0 INCHES.

| Specimen Number | Bonding Conditions | Bend Load at Failure | Flexural Strength | Percent of Parent Metal Strength |
|---|---|---|---|---|
| 3S-A | 1600°F-1 Hr.-100 psi | 227 lb | 44,900 psi | 17.8% |
| 5S-A | 1600°F-4 Hr.-100 psi | 472 | 120,900 | 48.0 |
| 2S-A | 1700°F-1 Hr.-100 psi | 754 | 186,500 | 74.0 |
| 6S-A | 1700°F-4 Hr.-100 psi | 812 | 200,800 | 79.7 |
| Parent Metal | Untreated | 1407* | 251,800* | 100.0 |

* Average of three specimens.

TABLE 3

SHEAR STRENGTH OF Ti-6Al-4V ALLOY DIFFUSION BONDED SPECIMENS
COMPARED WITH PARENT METAL STRENGTH

| Specimen Number | Bonding Conditions | Shear Strength of Joint (Avg. of 4 Tests) | Shear Strength of Parent Metal (Avg. of 4 Tests) | Deformation |
|---|---|---|---|---|
| 2 HP | 1640°F-1 Hr.-650 psi | 89,500 psi | 89,300 psi | 0.056" |
| 3 HP | 1540°F-1 Hr.-650 psi | 81,470 | 83,300 | 0.034" |
| LP 1 | 1470°F-½ Hr.-100 psi | 17,900 | 92,200 | 0.0025" |
| LP 2 | 1440°F-½ Hr.-100 psi | 24,150 | 95,200 | 0.0025" |

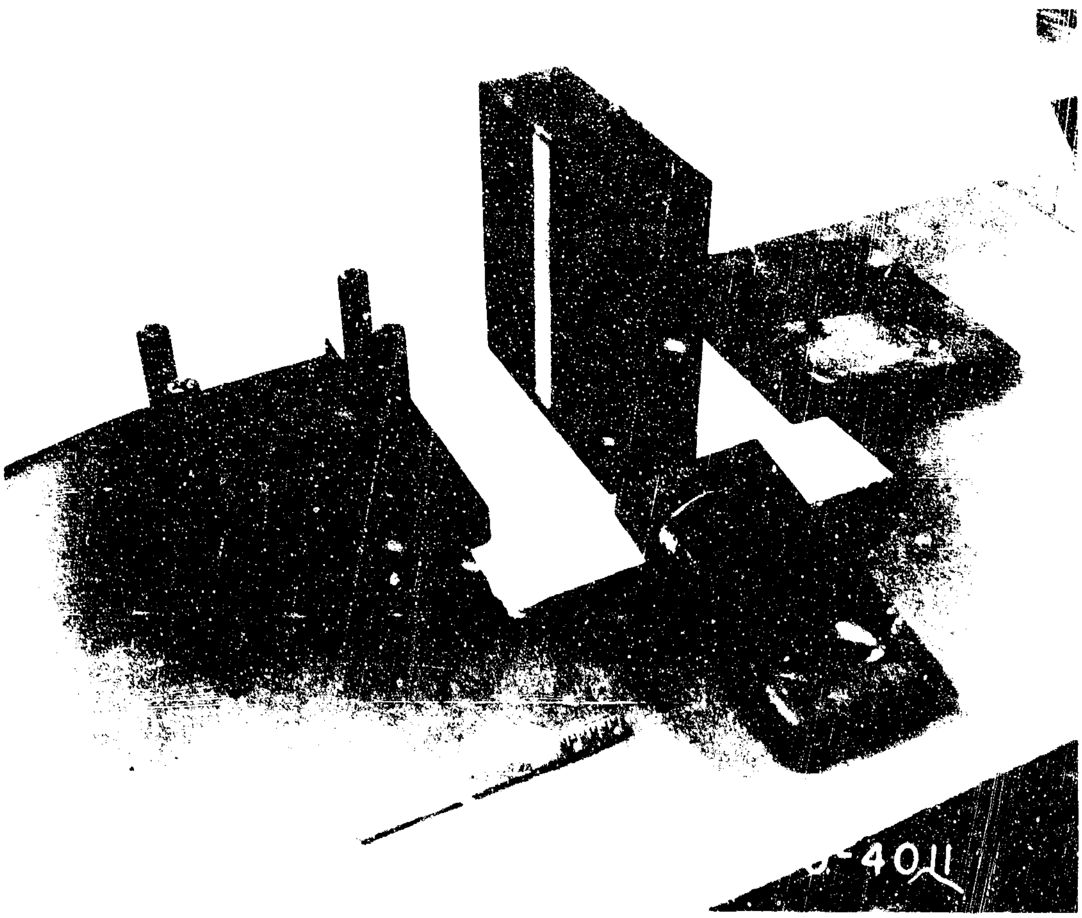

Figure 1. Details of Graphite Fixture with Bonded Specimens in Place

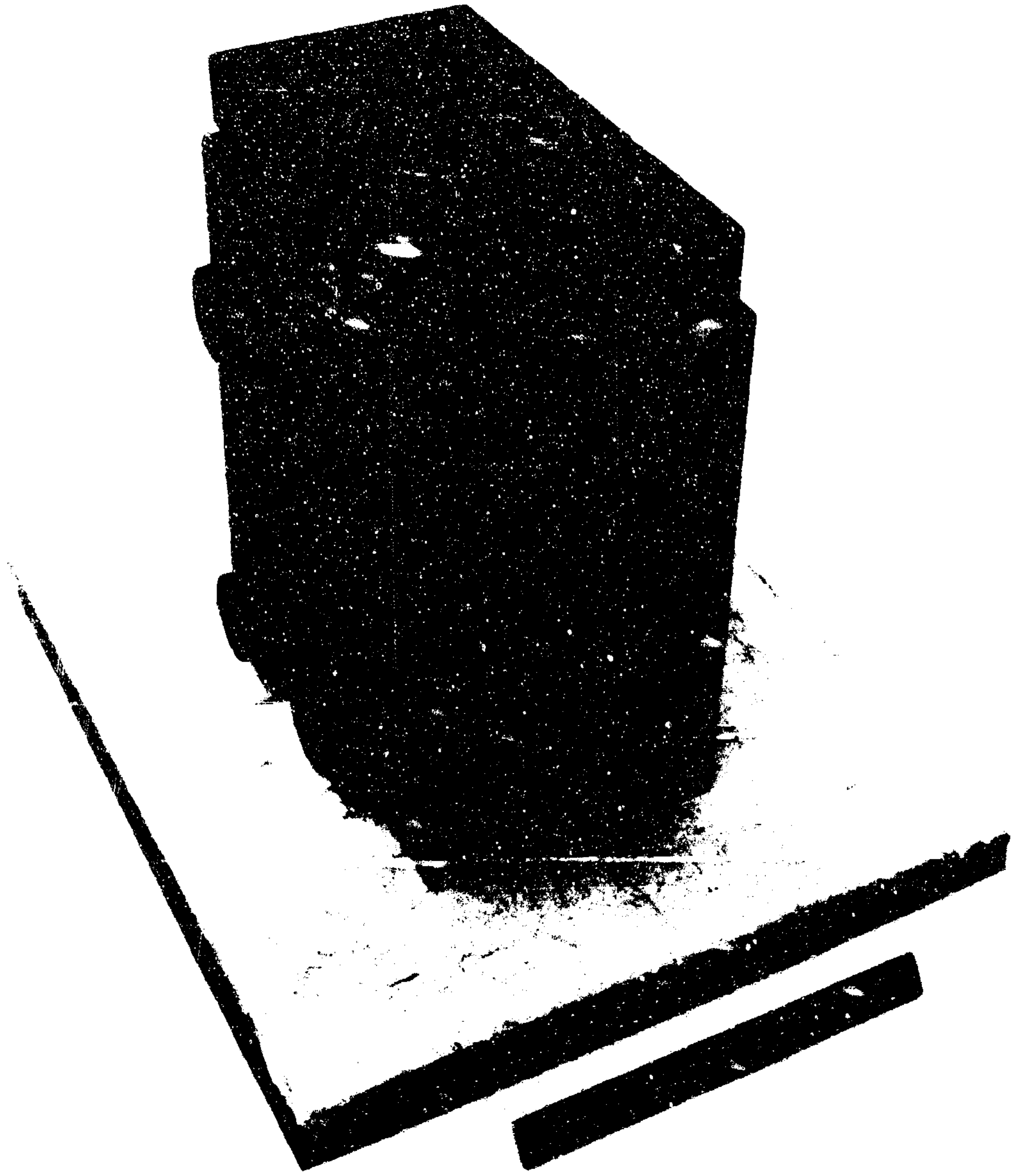

Figure 2. Assembled Graphite Butt Bonding Fixture with Top Plate in Place for Dead Weight Loading

Figure 3. Photograph of Ti-6Al-4V Alloy Specimens Before and After Butt Diffusion Bonding

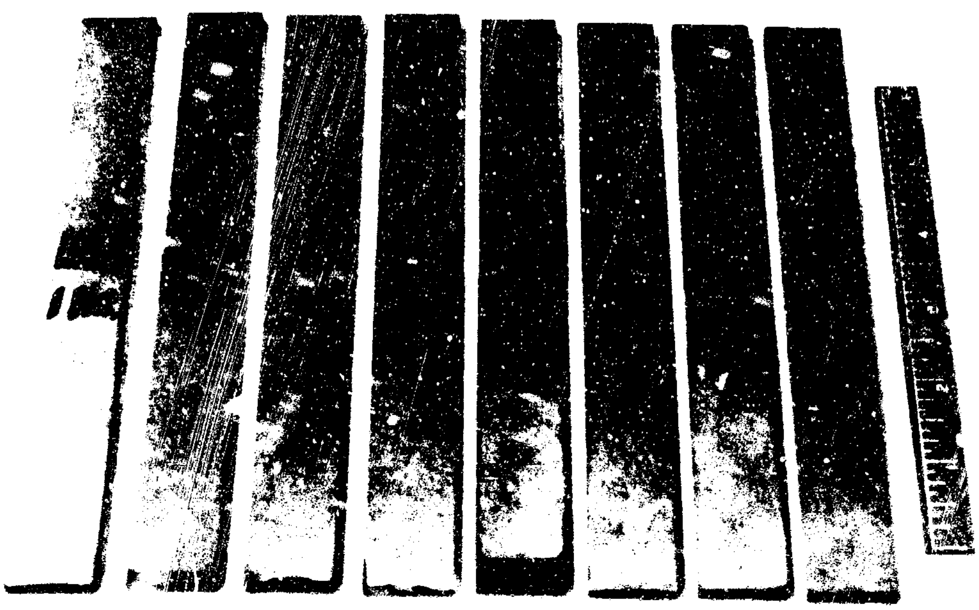

Figure 4. Photograph of Ti-6Al-4V Alloy Specimens After Butt Diffusion Bonding


Figure 5. Tensile Test Specimens Machined from Butt Diffusion Bonded Specimens

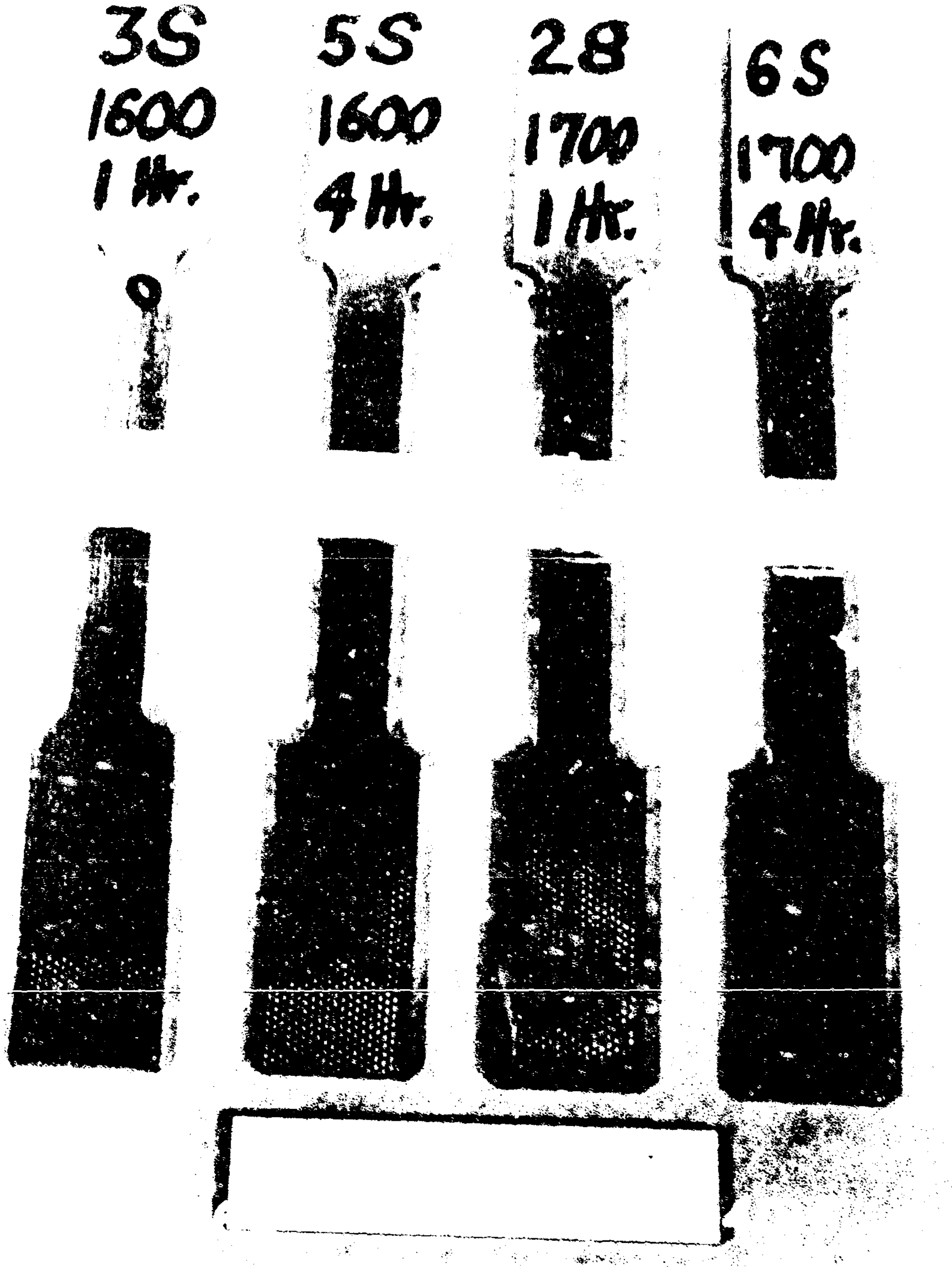


Figure 6. Butt Diffusion Bonded Specimens After Room Temperature Tensile Testing

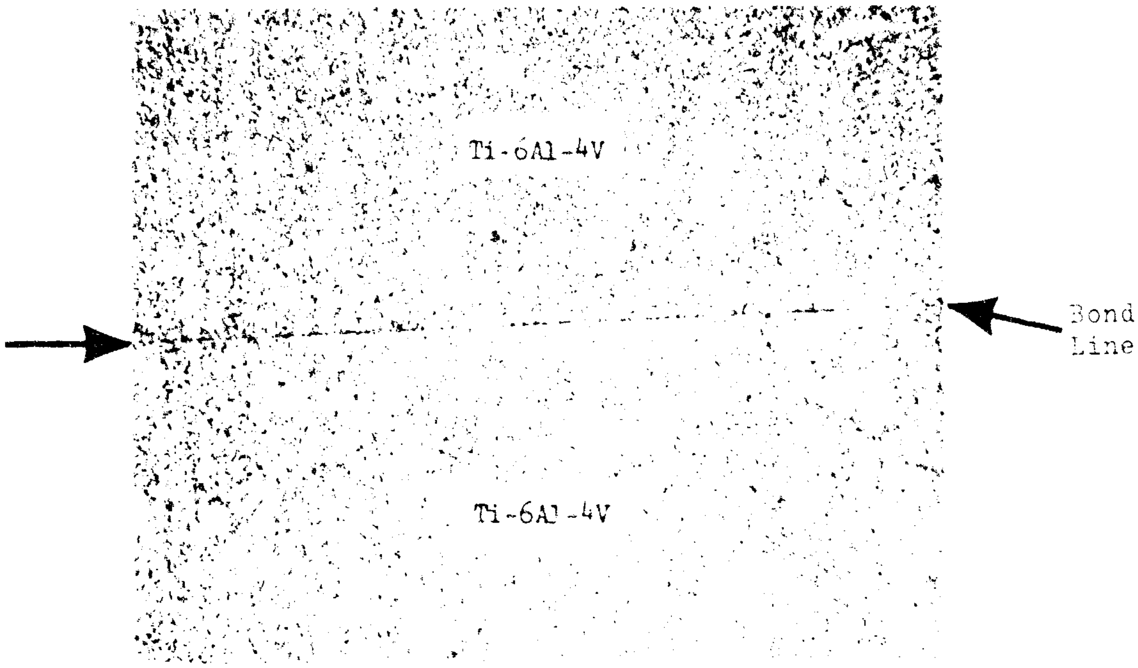


Figure 7. Run 38. Bonding at 1600°F; 100 psi; 1 Hour.
Tensile Strength: 49,700 psi.
Met.-7443-1-1. Etched. 100X.

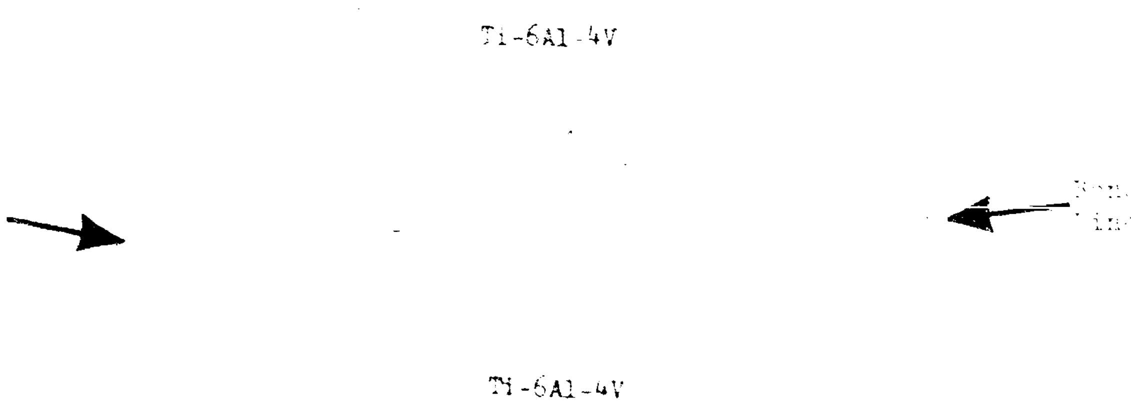


Figure 8. Run 5[illegible]. Bonding at 1600°F; 100 psi; 4 Hours.
Tensile Strength: 122,300 psi.
Met.-7443-2-1. Etched. 100X.

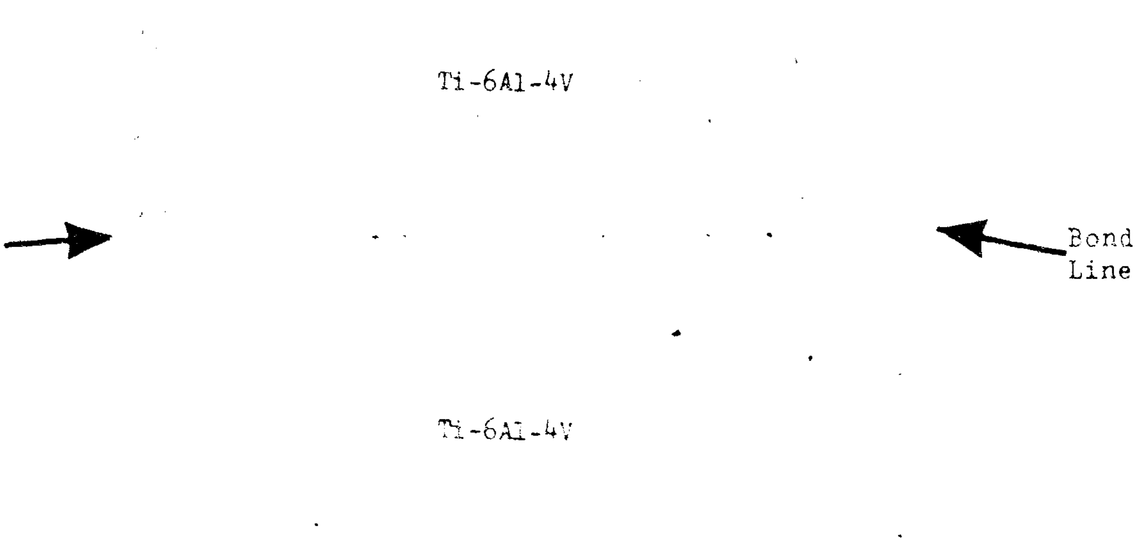


Figure 9. Run 28. Bonding at 1700°F; 100 psi; 1 Hour.
Tensile Strength: 133,200 psi.
Met.-7443-3-1. Etched. 100X.

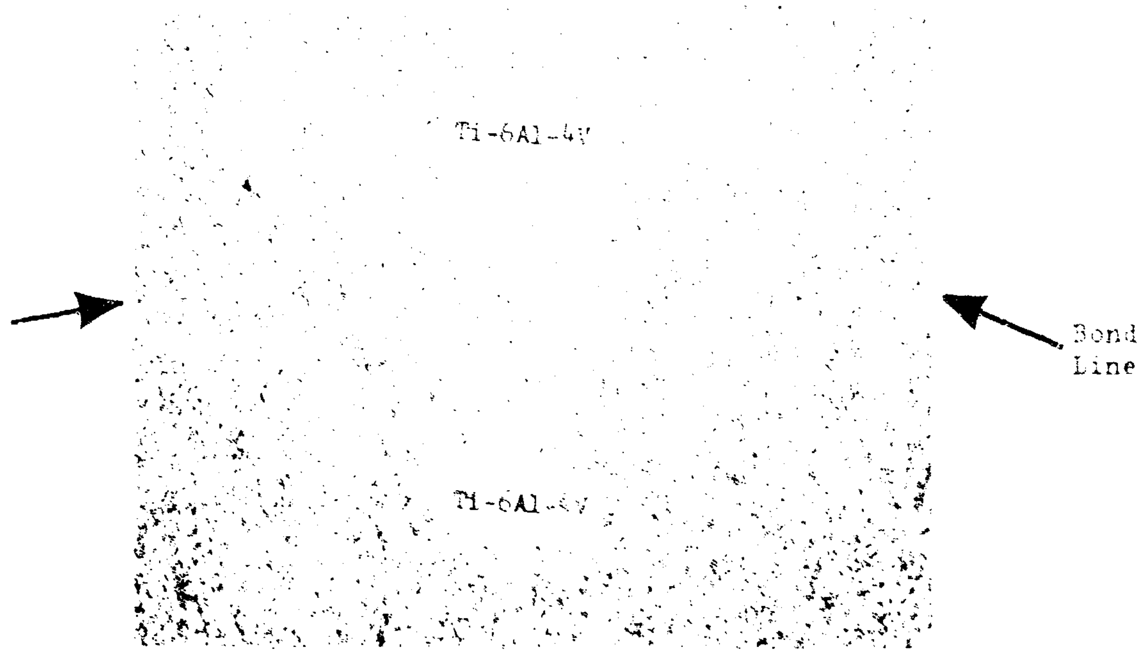


Figure 10. Run 68. Bonding at 1700°F; 100 psi; 4 Hours.
Tensile Strength: 137,500 psi.
Met.-7443-4-1. Etched. 100X.

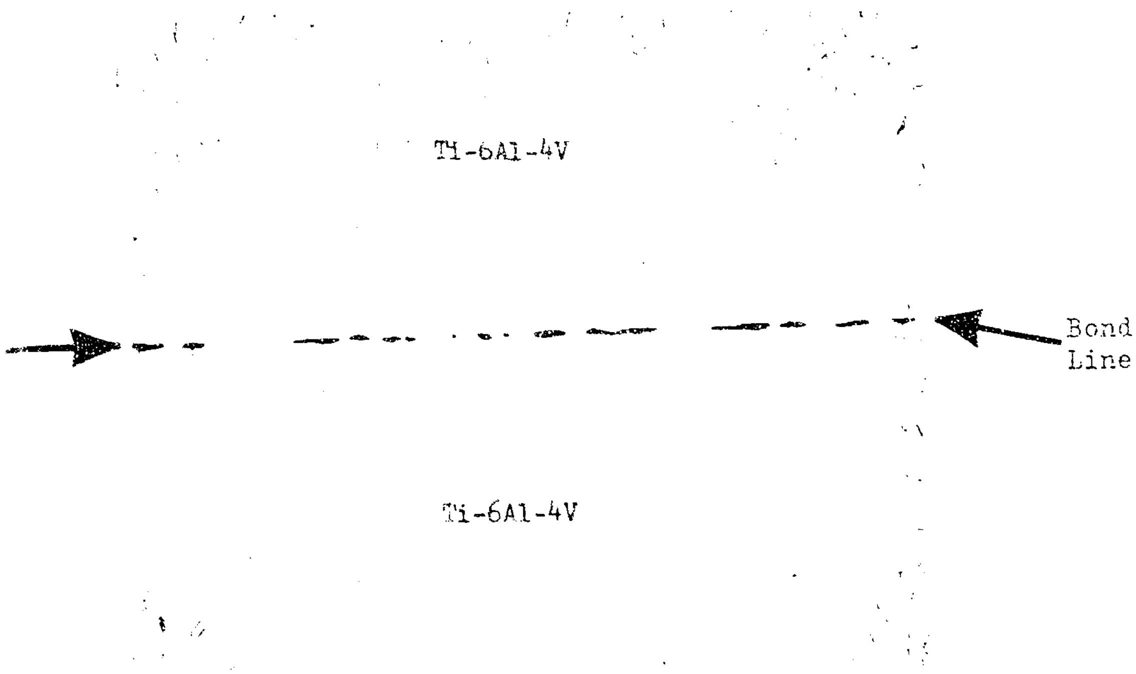


Figure 11. Run 3S. Bonding at 1600°F; 100 psi; 1 Hour.
Tensile Strength: 49,700 psi.
Met.-7443-1-2. Etched. 500X.

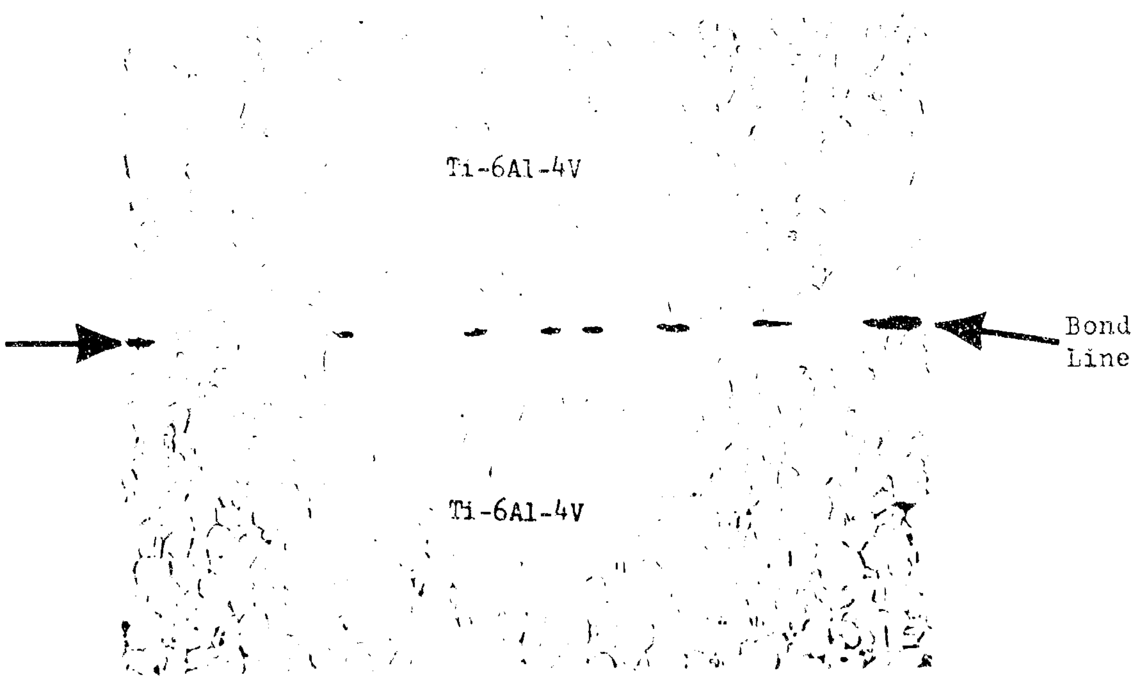


Figure 12. Run 5S. Bonding at 1600°F; 100 psi; 4 Hours.
Tensile Strength: 122,300 psi.
Met.-7443-2-2. Etched. 500X.

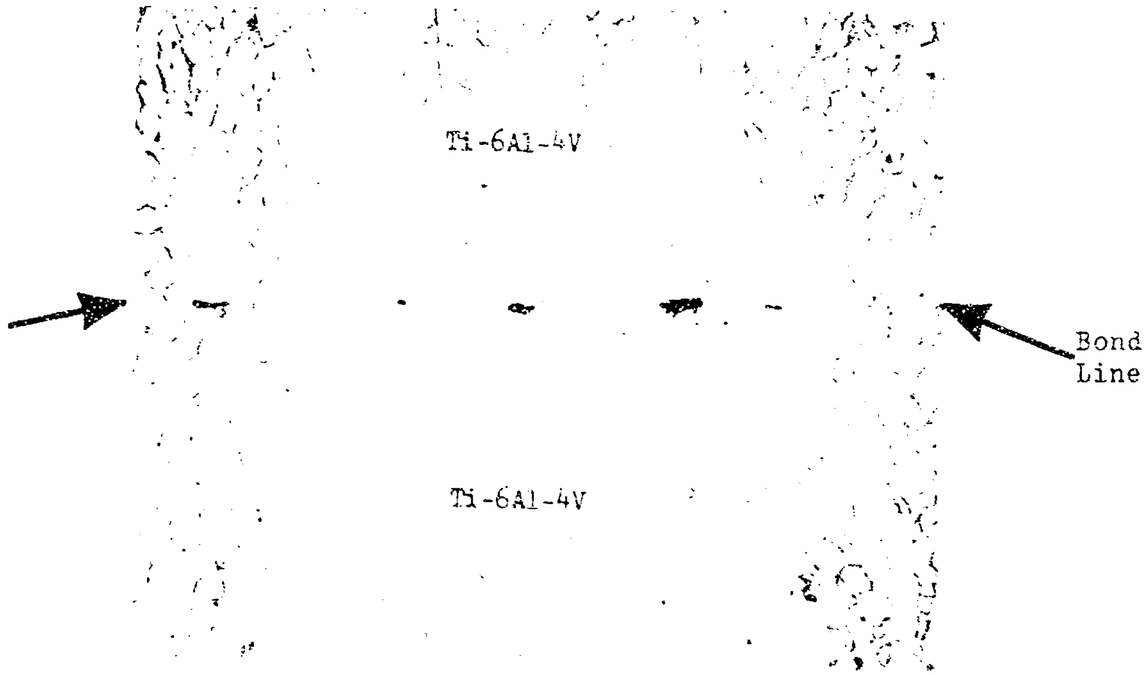


Figure 13. Run 2S. Bonding at 1700°F; 100 psi; 1 Hour.
Tensile Strength: 133,200 psi.
Met.-7443-3-2. Etched. 500X.


Figure 14. Run 6S. Bonding at 1700°F; 100 psi; 4 Hours.
Tensile Strength: 137,500 psi.
Met.-7443-4-2. Etched. 500X.

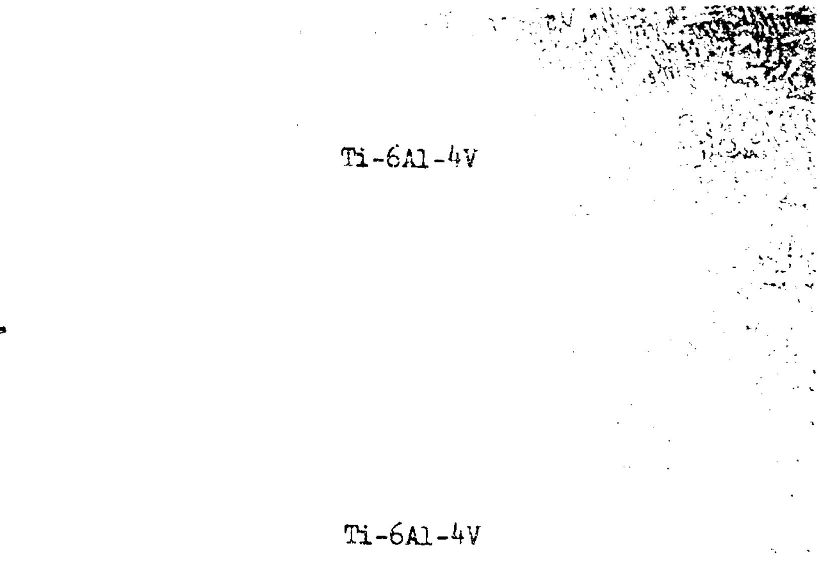


Figure 15. Run 2HP. Bonding at 1640°F; 650 psi; 1 Hour.
Shea Strength: 89,520 psi.
Met.-7444-1-1. Etched. 100X.

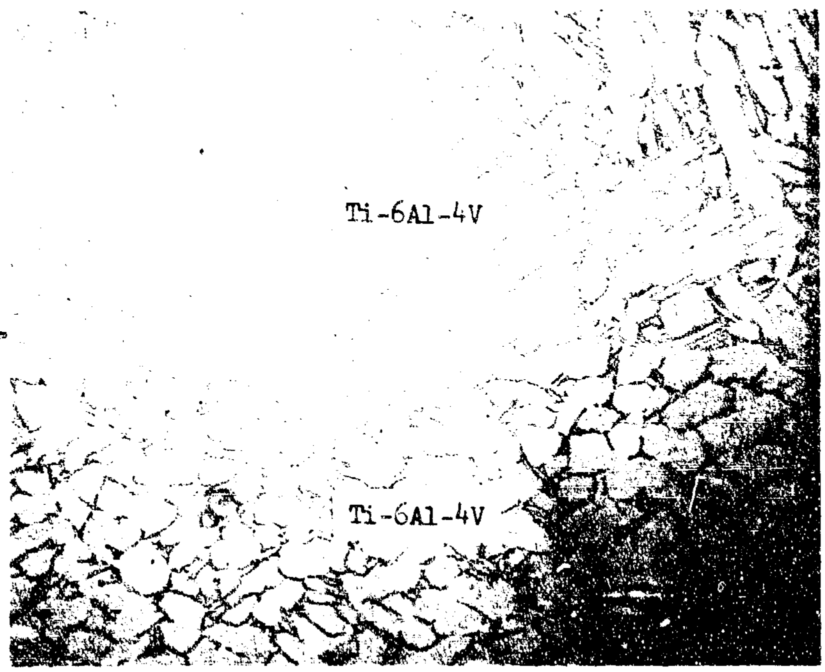


Figure 16. Run 2HP. Bonding at 1640°F; 650 psi; 1 Hour.
Shear Strength: 89,520 psi.
Met.-7444-1-2. Etched. 500X.

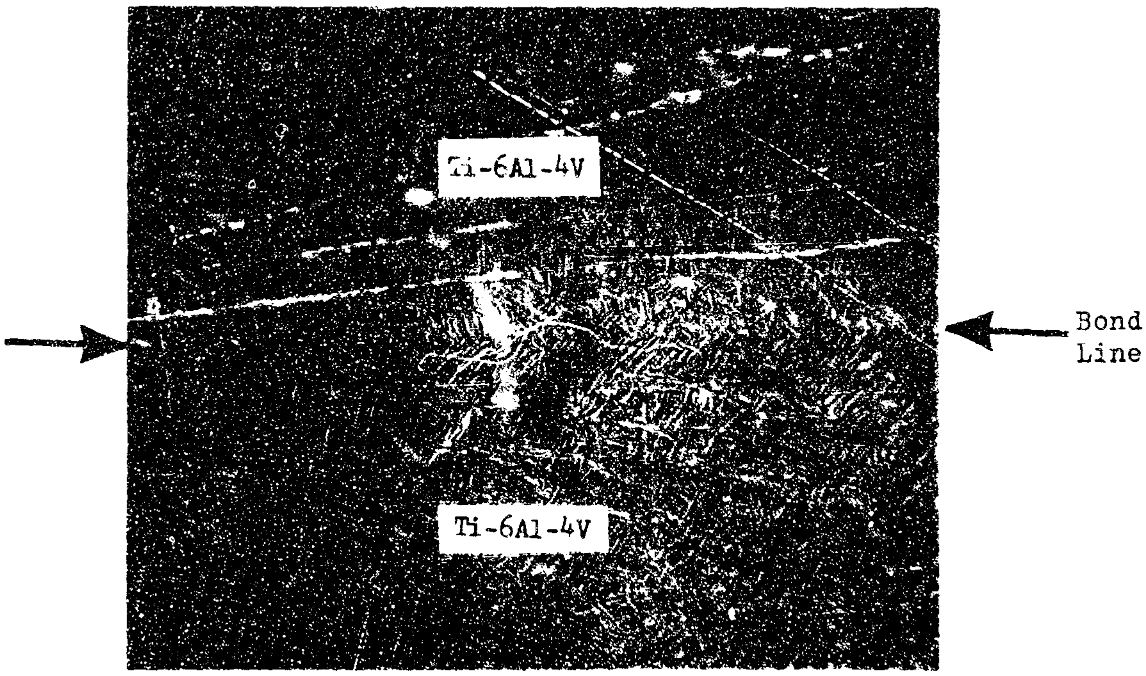


Figure 17. Run 3HP. Bonding at 1540°F; 65[illegible] psi; 1 Hour.
Shear Strength: 81,470 psi.
Met.-7444-2-1. Etched. 100X.


Figure 18. Run 3HP. Bonding at 1540°F; 650 psi; 1 Hour.
Shear Strength: 81,470 psi.
Met.-7444-2-2. Etched. 500X.

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13. ABSTRACT


The program attempts to develop an understanding of the diffusion bonding of titanium alloys; in particular, the alloy Ti-6Al-4V. The accomplishments of the third quarter of the program are as follows:

1) A series of tensile and bend tests has been completed. These tests showed trends which were in reasonable agreement with the shear tests performed during the second quarter.

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